PCT/GB00/03218

PATENT COOPERATION TREATY

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NOTIFICATION OF ELECTION

(PCT Rule 61.2)

From the INTERNATIONAL BUREAU

To:

Commissioner
US Department of Commerce
United States Patent and Trademark Office, PCT
2011 South Clark Place Room CP2/5C24
Arlington, VA 22202
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in its capacity as elected Office

Date of mailing (day/month/year) 26 April 2001 (26.04.01)	
International application No. PCT/GB00/03218	**Applicant's or agent's file reference** AMS.P50841PC
International filing date (day/month/year) 22 August 2000 (22.08.00)	**Priority date** (day/month/year) 02 September 1999 (02.09.99)
Applicant LAWS, Robert et al	

1. The designated Office is hereby notified of its election made:

[X] in the demand filed with the International Preliminary Examining Authority on:

07 March 2001 (07.03.01)

[ ] in a notice effecting later election filed with the International Bureau on:

2. The election [X] was

[ ] was not

made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer Juan Cruz Telephone No.: (41-22) 338.83.38

PATENT COOPERATION TREATY

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INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

12

Applicant's or agent's file reference AMS.P50841PC	FOR FURTHER ACTION	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
International application No. PCT/GB00/03218	International filing date *(day/month/year)* 22/08/2000	Priority date *(day/month/year)* 02/09/1999
International Patent Classification (IPC) or national classification and IPC G01V1/02		
Applicant GECO-PRAKLA (UK) LIMITED et al.		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 9 sheets, including this cover sheet.

   ☐ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of sheets.

3. This report contains indications relating to the following items:

   I ☒ Basis of the report
   II ☐ Priority
   III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   IV ☐ Lack of unity of invention
   V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   VI ☐ Certain documents cited
   VII ☒ Certain defects in the international application
   VIII ☒ Certain observations on the international application

Date of submission of the demand	Date of completion of this report
07/03/2001	02.01.2002
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Baumann, M Telephone No. +49 89 2399 2447

Form PCT/IPEA/409 (cover sheet) (January 1994)

I. Basis of th report

1. With regard to the **elements** of the international application *(Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17))*:
Description, pages:

1-20 as originally filed

Claims, No.:

1-29 as originally filed

Drawings, sheets:

1/10-10/10 as originally filed

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

These elements were available or furnished to this Authority in the following language: , which is:

- ☐ the language of a translation furnished for the purposes of the international search (under Rule 23.1(b)).
- ☐ the language of publication of the international application (under Rule 48.3(b)).
- ☐ the language of a translation furnished for the purposes of international preliminary examination (under Rule 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

- ☐ contained in the international application in written form.
- ☐ filed together with the international application in computer readable form.
- ☐ furnished subsequently to this Authority in written form.
- ☐ furnished subsequently to this Authority in computer readable form.
- ☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
- ☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

4. The amendments have resulted in the cancellation of:

- ☐ the description, pages:
- ☐ the claims, Nos.:

☐ the drawings, sheets:

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

   (Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.)

6. Additional observations, if necessary:

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-29
	No:	Claims	
Inventive step (IS)	Yes:	Claims	9-24,26-29
	No:	Claims	1-8, 25
Industrial applicability (IA)	Yes:	Claims	1-29
	No:	Claims	

2. Citations and explanations
   see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:
see separate sheet

VIII. Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:
see separate sheet

Re It m V (Novelty, inventive step, industrial applicability)

Reference is made to the following documents:

D1: US-A-5 469 404 (BARBER HAROLD P ET AL) 21 November 1995 (1995-11-21)

D2: GB-A-2 148 503 (SIESMOGRAPH SERVICE) 30 May 1985 (1985-05-30)

D3: GB-A-2 176 605 (EXXON PRODUCTION RESEARCH CO) 31 December 1986 (1986-12-31)

D4: WO 97 06452 A (HYDROACOUSTIC INC ;BOUYOUCOS JOHN V (US)) 20 February 1997 (1997-02-20)

D5: US-A-4 727 956 (HUIZER WILLEM) 1 March 1988 (1988-03-01)

D6: US-A-4 136 754 (MANIN MICHEL) 30 January 1979 (1979-01-30)

D7: US-A-4 493 061 (RAY CLIFFORD H) 8 January 1985 (1985-01-08).

- ## Negative Statements

1. **Lack of Inventive Step (Article 33(3) PCT, Rule 65.1 PCT)**

1.1. Claims 1, 3, and 7 are unclear. For the purpose of inventive step considerations, the claims have been interpreted as described in Item VIII below.

1.2. Claims 1-8 and 25 are not inventive. Document D1 is considered as the closest prior art. D1 discloses (the references in parentheses referring to D1):

1.3. **Claim 1:**

• a method for seismic surveying in marine environment
• using an array of seismic sources (air guns)
• from which seismic energy is emitted at one or more different depths (cf. Figure 1; abstract, column 2, lines 10-12; column 4, lines 2-7).

The differences between D1 and claim 1 of the present international application are:
(a) In D1, air guns are used as seismic energy sources instead of marine vibrators.
(b) In D1, no "sweep" is produced with the air guns, whereas in the application, a sweep as an output signal is produced with the vibrators.

The problem to be solved can therefore be considered as how to provide a surveying method using a seismic source with which a controlled output signal with a frequency bandwidth can be produced.

(a) The use of an array of vibrators is well known in the art of seismic surveying: Documents D1-D7 all show the use of arrays of seismic sources in marine environment. Vibrators are only one of a few possible seismic energy sources in exploration seismics from which a person skilled in the art would choose from.
(b) The emission of seismic energy in form of a sweep signal employing a vibrator is also well known in seismic surveying, especially in land seismics. The skilled person in the art would consider to apply the general common knowledge of land to marine seismics when confronted with the problem of generating a controlled output wave train and employ an array of marine vibrators able to emit a sweep signal.

The subject-matter of claim 1 is therefore not inventive.

For the sake of completeness, it is mentioned that D2-D7 also describe methods of seismic surveying employing arrays of sources emitting energy at different depths:
- D2: array of implosive marine sources (abstract, page 1, line 9 and lines 78-80);
- D3: arrays of air guns (abstract; page 1, line 65; page 2, lines 30-31; page 6, lines 7-8);
- D4: array of air guns, spark sources (abstract; page 4, lines 23-28);
- D5: arrays of air guns (abstract; Figures 1, 4a, 4b);
- D6: plurality of seismic sources (abstract; Figure 2; page 8, line 67-page 9, line 1);
- D7: gas expansion marine source or air guns (abstract; Figures 5 and 7; column 3, lines 33-45).

1.4. **Independent claim 6 (arrangement):**
Claim 6 defines a standard arrangement used in marine seismics. The following components of the arrangement are also disclosed in D1 or are implicitly employed with the arrangement discussed therein (cf. Figure 1): a vessel, source of seismic energy, ie. an array of two or more marine sources, suspended so that a first source of the array is situated at a first depth and a second source is disposed at a second greater depth.

The difference between D1 and claim 6 of the present application is that in D1, arrays of air guns are used, whereas in the application marine vibrators are used as seismic sources. The associated problem/solution has already been discussed in 1.3(a), above.

Claim 6 is therefore not inventive.

The basic components of the arrangement (vessel, array of seismic sources, relative position of a first and second seismic source of an array) are also shown in D2-D7 or are implicitly included in the surveying arrangements employed therein: D2: page 1, line 113-123; D3: page 6, lines 3-12; claim 1; D4: Figure 22; D5: Figure 1; abstract; Figures 4a and

4b: sources at different depths; D6: Figure 2; claim 1; D7: Figure 5.

1.5. **Independent claim 25 (arrangement):**
The basic components of the claimed marine seismic acquisition arrangement are also disclosed in D1 or are implicitly employed with the arrangement described therein (cf. also Figure 1 and discussion about claim 6, above).

The difference between D1 and claim 25 of the present application is that the arrangement of D1 includes neither a control means for varying the depth of the seismic sources nor a control means for controlling the emission of seismic energy.

A control means which allows to move and position seismic sources to a desired depth is however described in D3 (D3: page 3, line 6 and lines 45-48). The skilled person in the art would know how to adapt the arrangement of D1 to include a control means as described in D3 to arrive at the claimed arrangement. Additionally equipping the arrangement of D1 with a second means for controlling the seismic sources to emit energy is considered obvious in the art of seismic exploration.

Claim 25 does therefore not involve an inventive step.

1.6. **Dependent claims 2-5 and 7-8** are not inventive because the person skilled in the art would consider the teaching of document D1 in combination with that of one of the documents D2-D7 or apply general common knowledge to arrive at the claimed subject matter:

Claim 2: In D1, the energy is also emitted from an array of sources, where a first source is located a first depth and a second source is located at a second greater depth (Figures 1-3, 5-6; abstract; column 4, lines 2-7). Air guns are used in D1 instead of vibrators, this difference and associated problem/solution has been discussed in 1.3(a), above.

Marine seismic sources positioned at different depths and from which energy is emitted are also disclosed in documents D2-D7: D2: abstract; page 1, lines 78-84; D3: Figure 1; D4: "Vertical array", page 4, line 23; Figure 8; D5: Figure 4a, and 4b; D6: "placed at various depths": column 9, line ; Figures 2 and 6; D7: column 3, lines 35-40.

Claim 3 (method) and corresponding claim 7 (arrangement):
In D7, the individual sources are displaced laterally and vertically with respect to each other (cf. D7: column 3, lines 33-45; Figures 5 and 7). The energy emitted from gas expansion sources can irradiate in all directions. In the case of a configuration as

described in D7, a first source of the array (eg. S1 in Figure 7 of D7) is displaced with respect to the second source (eg. S2 or S3 in Figure 7 of D7) in direction of emission of the seismic energy.

Dependent claims 4 and 5: D1 (column 8, lines 2-10) and D2 (abstract) also describe methods wherein the emission of seismic energy at a second seismic source is started at a pre-determined time after the starting of emission at a first source. In D1 (column 8, lines 2-10) this pre-determined time is also equal the travel time necessary for the energy (wave front) to travel from the first source to the second source.

Dependent claim 8: D1 (cf. Figures 3 and 5), D3 (cf. Figure 1), D5 (cf. Figure 1), and D6 (cf. Figures 2 and 6) show arrangements wherein the arrays include four to six seismic sources. The use of marine vibrators instead of any other seismic sources does not involve an inventive step (see argumentation under 1.3.(a))

• Positive Statements

2. Inventive Step (Article 33(3) PCT, Rule 65.1 PCT)

2.1. The independent method claim 11 is unclear. For the purpose of inventive step considerations, it has been interpreted as described in Item VIII below.

2.2. The closest prior art document D1 shows a method for seismic surveying in marine environment using an array of seisimc sources. The air guns are operably fixedly arranged at different water depths and fired at different times to improve the characteristics of seismic source signals. **In the independent method claim 11**, the preferred depths for an array of seisimc sources is calculated by performing a spectral analysis of the emitted energy at the array of sources.

The subject-matter of claim 11 differs from that of D1 in that:
• for each source of the array for which a depth has initially been attributed, a amplitude spectrum of the source signal is performed, and
• all the amplitude spectra of each source is summed to obtain the total spectrum for the array of sources.

D2 describes a method of seismic surveying where by choosing an appropriate size of air gun firing chamber or by adjusting the depth of the array (D2: page 1, lines 19-23) the directivity of the emitted source signal is adjusted.

Although spectral analysis of seismic energy is known in the art of seismic data processing and although it is known from D2 that depths at which seismic sources are placed have an influence on the directivity and the characteristics of the emitted signal, the prior art (D1-D7) does not teach nor suggest to calculate the preferred source depths by parametrizing the amplitude spectra in a manner as claimed.

By placing the array of sources at preferred depths during the survey, a constructive interference occurs at all frequencies which leads to an increased amplitude at all frequencies.

Claim 11 therefore new and inventive in the sense of Article 33(2) and (3) PCT.

2.3. **Claims 12-18** are dependent on claim 11 and as such also meet the requirements of the PCT with respect to novelty and inventive step.

2.4. **Dependent claims 9 and 10** define particular layouts of arrays of vibrators which are not suggested in nor rendered obvious by the prior art D1-D7. Therefore, claims 9 and 10 meet the requirements of the PCT with respect to novelty and inventive step.

2.5. **Dependent claims 19-24** define seismic surveying methods comprising the steps of varying the depth of the vibrators or the frequency of the emitted energy from the marine vibrators in a particular manner while the energy is emitted. These steps are not suggested in nor rendered obvious by the prior art D1-D7. Claims 19-25 therefore meet the requirements of the PCT with respect to novelty and inventive step.

2.6. **Dependent claims 26-29** define that the control means for varying the depth of the marine vibrator is adapted to control the depth on the basis of the wavelength of the emitted energy. The prior art does not teach nor suggest to adapt the depth of vibrators as a function of the wavelength of the emitted energy. Therefore, claims 26-29 depending on claim 25 meet the requirements of the PCT with respect to novelty and inventive step.

3. Industrial applicability (Article 33(4) PCT

All claims 1-29 are doubtless industrially applicable.

Re Item VII (Certain defects)

1. The features of the claims are not provided with reference signs placed in parentheses (Rule 6.2(b) PCT).
2. Contrary to the requirements of Rule 5.1(a)(ii) PCT, the relevant background art disclosed in the documents of the international search report is not mentioned in the description, nor are these documents identified therein.
3. a document reflecting the prior art described on page 1-4, is not identified in the description (Rule 5.1(a)(ii) PCT).
4. The labels (a) and (b) characterizing the two different curves in Figure 10 are missing (see also description on page 8).

Re Item VIII (Certain observations)

1. Unclarities (Article 6 PCT)

1.1. **Claim 1:** it is not clear whether the term "sweep" refers to the controlled frequency characteristics of the emitted signal over a certain time or whether "sweep" refers to the time during which energy is emitted. It is also unclear whether a sweep is emitted at one or all (more) vibrators.
The claim is interpreted as follows: the method of seismic surveying using one or more marine vibrators comprising emitting seismic energy in form of a sweep signal of a certain time length at one or more vibrators located at different depths.

1.2. **Claims 3 and 7:** The active term "is displaced" could suggest that the first vibrator of the array is moved with respect to the second vibrator during energy emission, the movement taking place in the direction of emission of seismic energy. It is not clear whether their relative position of the vibrators is changed <u>during</u> emission of energy or not.
The claims are interpreted in the light of the description in the sense that the relative position of the vibrators is fixed during emission of energy, but that the first vibrator is located relative to the second vibrator in the direction of the wave front, ie energy direction.

1.3. **The method claim 11** appears to be incomplete: steps (a) to (d) do not result in the calculation of the preferred depth for seismic sources.
The claim is interpreted as follows: To calculate the preferred depths for the seismic sources in an array, steps (a) to (d) are repeated until an acceptable value for the parameter is obtained.

S2.5017

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(71) Applicant *(for all designated States except US)*: GECO-PRAKLA (UK) LIMITED [GB/GB]; Schlumberger House, Buckingham Gate, Gatwick Airport, Gatwick, Sussex RH6 0NZ (GB).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: LAWS, Robert [GB/GB]; 86 Kimberley Road, Cambridge, Cambridgeshire CB4 1HJ (GB). MORICE, Stephen Patrick [GB/GB]; 6 Murray Road, Wokingham, Berkshire RR41 2TA (GB).

(74) Agent: SUCKLING, Andrew Michael; Marks & Clerk, 4220 Nash Court, Oxford Business Park South, Oxford, Oxfordshire OX4 2RU (GB).

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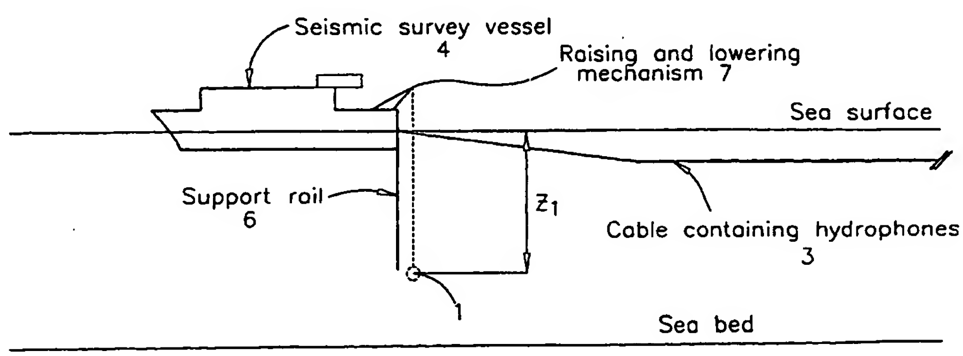
Published:
— *With international search report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: A METHOD OF SEISMIC SURVEYING, A MARINE VIBRATOR ARRANGEMENT, AND A METHOD OF CALCULATING THE DEPTHS OF SEISMIC SOURCES



(57) Abstract: A method of seismic surveying comprises emitting seismic energy at two or more different depths during a sweep. In one embodiment, the depth of a seismic source is varied during a sweep, by raising or lower the source while it is emitting seismic energy. In another embodiment, an array of two or more marine vibrators is used as the source of seismic energy, with the vibrators in the array being disposed at different depths. The invention allows notch frequencies in the amplitude spectrum to be eliminated, and allows improvements in both the spectral flatness and the amplitude at low frequencies.

WO 01/16621 A1

A method of seismic surveying, a marine vibrator arrangement, and a method of calculating the depths of seismic sources

The present invention relates to a method of marine seismic surveying, and in particular to a method in which seismic energy is emitted at different depths during a survey. The present invention also relates to a marine seismic surveying arrangement for carrying out such a method, and to a method of calculating the preferred depths for emitting seismic energy.

The principle of marine seismic surveying is shown schematically in Figure 1. Seismic energy is emitted in a generally downwards direction from a source of seismic energy 1, is reflected by the sea bed 2 and by the earth strata or geological structures beneath the sea bed, and is received by an array of seismic receivers 3 such as hydrophones. Analysis of the energy received at the receiving array 3 can provide information about the earth strata or geological structures beneath the seabed. The source of seismic energy 1 is suspended at a fixed depth *z* from a survey vessel 4.

One suitable source of seismic energy for use in marine seismic surveying is the marine vibrator. In operation, the frequency of seismic energy emitted by a marine vibrator is varied, or "swept", in a well-defined manner during each operation, or "sweep", of the vibrator. The construction and operation of this device is described in Baeten et al in "First Break" Vol 6, No. 9, pp. 285-294 (1988) and by Haldorsen et al in "Expanded abstracts of the Fifty Fifth Meeting of the Society of Exploration Geophysicists" pp. 509-511 (1985).

When marine vibrators are used as the source of seismic energy in marine seismic surveying, an array of vibrators distributed in a horizontal direction is generally used. The vibrators in the array are suspended at a fixed common depth beneath suitable floats. The array is towed behind the vessel at about 5 knots. The vibrators are distributed perpendicularly to the direction of tow and are operated periodically, for example every 20 seconds or so to produce their respective 8 to 15 second swept frequency outputs.

One problem associated with conventional marine seismic surveying using a marine vibrator as the seismic source is that the downwardly directed seismic wave is the sum of two signals. In addition to the direct signal from the vibrator (otherwise known as the "vibrator output"), there is also a reflected signal from the sea surface. The signal reflected from the sea surface, known as a "ghost" signal, is delayed relative to the direct signal. There are two components to this delay: firstly, there is a 180° phase change upon reflection at the sea surface and, secondly, there is a time delay corresponding to the additional path length (which for a signal emitted in the vertical direction is $2z$, or twice the depth of the vibrator).

The actual vertical far field signal is the sum of the direct signal and the ghost signal. The direct signal and the ghost signal will interfere, and this causes variations in the amplitude of the far field signal. For some frequencies, the interference is destructive and causes a zero amplitude or "notch" in the spectrum. This occurs at frequencies where the depth of the source is an even number of quarter wavelengths:

$$f_{\text{notch}} = (nc/2z),\ n = 0, 1, 2, 3... \tag{1}$$

In equation 1, c is the speed of sound in water, and n is an integer giving the harmonic order.

Constructive interference occurs at frequencies exactly intermediate adjacent notch frequencies, and this leads to maxima in the amplitude at these frequencies, given by:

$$f_{\text{peak}} = (2n + 1)c/4z,\ n = 0, 1, 2, 3\ldots \tag{2}$$

The effect of the interference between the direct signal and the ghost signal can be thought of as applying a frequency domain "ghost filter" to the direct signal. The ghost filter has the following form:

$$g(f) = 1 + |r|^2 - 2|r|\cos(2zf/c) \tag{3}$$

In equation (3), r is the reflection coefficient at the sea surface. The amplitude spectrum of the ghost filter resembles a full-wave rectified sine wave, with zeros at the ghost notch frequencies and peaks of amplitude 2.0 (6 dB) at the peak frequencies.

Figure 2 shows the amplitude of a typical ghost filter as a function of frequency. This figure shows the ghost filter for the case z = 12m, c = 1500m/s, and with a reflection coefficient of -1.0 at the sea surface. It will be seen that the amplitude decreases to 0 at the notch frequencies of 0Hz, 62.5Hz, 125Hz..., and that there are maxima in the amplitude at the peak frequencies of 31.25Hz, 93.75Hz...

The presence of maxima and minima in the far-field signal is undesirable. A further undesirable effect is the gradual roll-off that occurs near a notch frequency, and in particular near the zero-frequency end of the spectrum (a frequency of 0Hz is always a notch frequency).

One conventional approach to mitigating the problems caused by the notch frequencies is to deploy the vibrator at a fixed depth which is chosen such that the first non-zero notch frequency is placed just above the top of the frequency band of interest during the survey. The ghost filter obtained in this case is shown in Figure 3(a). This figure assumes that the depth of the seismic source is 5m, which is a typical depth.

Although the ghost filter shown in Figure 3(a) does not contain any notch frequencies within the spectrum, there is severe attenuation of the amplitude at frequencies below about 25Hz and above about 125Hz.

Figure 3(b) shows the effect on the amplitude of the ghost filter when the depth of the source in Figure 3(a) is increased from 5m to 50m. It is generally unsatisfactory to use a seismic source at such a depth, because notch frequencies occur around every 15Hz. However, this approach does improve the low frequency response, for example at around 8Hz.

A typical frequency range for a seismic survey is 5 to 85Hz. Figure 4 shows the effect of the "ghost filter" on the amplitude spectrum of an ideal linear seismic sweep. The trace (a) in Figure 4 shows the amplitude spectrum of a marine vibrator output, and it will be seen that the amplitude is substantially constant between approximately 10 and 75Hz.

The trace (b) in Figure 4 shows the amplitude spectrum of the seismic energy after interference between the direct signal and the ghost signal. That is, trace (b) represents the results of filtering trace (a) using the 'ghost filter'. It has been assumed that the depth of the source is $z = 6$m, so that the "ghost filter" applicable in this case is the one shown in Figure 2. More formally, trace (b) in Figure 4 represents the convolution of the trace (a) in Figure 4 with the ghost filter shown in Figure 2. It will be noted that the amplitude of the seismic energy spectrum at low frequencies (5-20Hz) has been attenuated as a result of the interference with the ghost signal – this is due to the presence of the 0Hz notch frequency. Conversely, the amplitude at higher frequencies has been increased, by a maximum of 6 dB at a frequency of 62.5Hz.

One prior art approach to overcoming the problem of this attenuation at low frequencies owing to the roll-off into the 0Hz notch frequency is to use a seismic energy source having greater amplitude at low frequencies. This approach has been commonly used with air gun sources. However, it is difficult to increase the amplitude at low frequencies when the seismic source is a marine vibrator, owing to mechanical constraints within the marine vibrator (and specifically, displacement limitations at low frequencies). This prior art approach cannot, therefore, be applied to the case where the energy source is a marine vibrator.

A further problem with conventional marine seismic surveying is that the reflectivity of the seabed is not independent of frequency. It has been found that the reflectivity of the seabed decreases as the frequency of the seismic energy increases. This effect is known as "earth loss filtering".

Figure 5 shows the effect of earth loss filtering on a typical seismic energy spectrum. In this example, the earth loss filtering is modelled by a Q-filter corresponding to a loss of 0.5dB/Hz. Trace (a) in Figure 5 shows the vibrator output after convolution with a ghost filter, and trace (b) shows the spectrum after earth loss filtering. It will be noted that the amplitude at high frequencies has been severely attenuated by the earth loss filter. In consequence, it is mainly the low frequency part of the energy spectrum that is left to provide useful information, and it is thus desirable to increase the amplitude of the low frequency part of the energy spectrum.

A first aspect of the present invention provides a method of seismic surveying using one or more marine vibrators, the method comprising emitting seismic energy at one or more different depths during a sweep.

According to the invention, during the course of a seismic sweep, seismic energy is emitted at two or more different depths. Energy emitted at one depth will have a different ghost filter from the energy emitted at another depth. It is accordingly possible to increase the amplitude of the energy spectrum at low frequencies.

In a preferred embodiment the method comprises emitting seismic energy from an array of marine vibrators, the array of marine vibrators comprising at least a first vibrator at a first depth and a second vibrator at a second depth greater than the first depth.

In an alternative preferred embodiment the method comprises varying the depth of a marine vibrator while the marine vibrator is emitting energy.

A second aspect of the present invention provides a seismic surveying arrangement comprising: a vessel; a source of seismic energy; and means for suspending the source of seismic energy from the vessel; wherein the source of seismic energy is an array of two or more marine vibrators, the array being suspended in use such that a first vibrator is disposed at a first depth and a second vibrator is disposed at a second depth greater than the first depth.

A third aspect of the present invention provides a method of calculating the preferred depths for seismic sources in an array of a plurality of seismic sources, the method comprising the steps of:

a) assigning a depth to each seismic source in the array;
b) for each seismic source in the array, obtaining the amplitude spectrum of seismic energy emitted by the seismic source;
c) summing the results of step (b) to obtain the amplitude spectrum of seismic energy emitted by the array of seismic sources; and
d) generating a parameter indicative of a property of the amplitude spectrum of seismic energy emitted by the array of seismic sources.

A fourth aspect of the present invention provides a seismic surveying arrangement comprising: a vessel; a marine vibrator; means for suspending the marine vibrator from the vessel; a first control means for causing the marine vibrator to emit seismic energy; and a second control means for varying the depth of the marine vibrator.

Preferred features of the invention are set out in the dependent claims.

Preferred embodiments of the present invention will now be described by way of illustrative examples, with reference to the accompanying figures in which:

Figure 1 is a schematic view of a conventional arrangement for a marine seismic survey;

Figure 2 shows the amplitude spectrum of a ghost filter corresponding to a depth of 12m;

Figure 3(a) shows the amplitude spectrum of a ghost filter corresponding to a depth of 5m;

Figure 3(b) shows the amplitude spectrum of a ghost filter corresponding to a depth of 50m;

Figure 4(a) shows the amplitude spectrum of a marine vibrator output;

Figure 4(b) shows the effect of convolving the amplitude spectrum of Figure 4(a) with a ghost filter;

Figure 5(a) shows the amplitude spectrum of a marine vibrator output after convolution with a ghost filter;

Figure 5(b) shows the amplitude spectrum of Figure 5(a) after convolution with an earth loss filter;

Figure 6 shows a marine seismic surveying arrangement of one embodiment of the invention at the start of a sweep;

Figure 7 shows the marine seismic surveying arrangement of Figure 6 at the end of a sweep;

Figure 8(a) shows the amplitude spectrum for an array of six marine vibrators at depths chosen to maximise the amplitude at low frequency;

Figure 8(b) shows the amplitude spectrum for an array of six vibrators at depths chosen to maximise spectral flatness;

Figure 8(c) shows the amplitude spectrum of an array of marine vibrators at depths chosen to optimise the amplitude at low frequency and the spectral flatness;

Figure 8(d) shows the amplitude spectrum for a conventional array of six vibrators at a depth of 6m;

Figure 9(a) shows the amplitude spectrum of an array of six marine vibrators at depths chosen to optimise the amplitude at low frequency and the spectral flatness using a biased summation;

Figure 9(b) shows the amplitude spectrum of an array of six marine vibrators at depths chosen to optimise the low frequency amplitude and the spectral flatness using an unbiased summation;

Figure 9(c) shows the amplitude spectrum of a conventional array of six vibrator units at a depth of 6m;

Figure 10(a) shows the trace of Figure 9(a) after convolution with an earth loss filter;

Figure 10(b) shows the convolution of the trace of Figure 9(d) with an earth loss filter; and

Figure 11 is a schematic illustration of a marine seismic surveying arrangement according to another embodiment of the present invention.

In one embodiment of the invention, the seismic source consists of a single marine vibrator, or of an array of marine vibrators arranged at a common depth. In this embodiment, emission of seismic energy at two or more depths is achieved by varying the depth of the marine vibrator(s) during a sweep.

Typically, a marine vibrator is used to generate a signal that sweeps in frequency across a frequency band of interest. In this embodiment of the invention, the depth of the vibrator, or array of vibrators, is varied during the sweep such that constructive interference, or partial constructive interference, is obtained during the whole duration of the sweep.

Figures 6 and 7 illustrate a marine seismic surveying arrangement at the start of a sweep according to this embodiment of the invention and at the end of a sweep according to this embodiment of the invention. In Figure 6, the vibrator is at a large depth z_1, at the start of a sweep. As the sweep progresses, the depth of the vibrator is decreased, reaching a minimum depth z_2 at the end of the sweep as shown in Figure 7.

In one preferred embodiment, the depth of the vibrator is varied as the frequency of energy emitted from the vibrator is varied such that the ratio between the depth of the vibrator and the wavelength of the energy being emitted is substantially constant. The ratio is preferably set to a value that provides constructive interference between the direct signal and the ghost signal. This can be achieved, for example, by setting the depth of the vibrator to be always approximately equal to one quarter of the wavelength of the energy being emitted.

If the sweep is, for example, from 7.5Hz to 75Hz, then the depth of the vibrator could initially be approximately 50m. During the sweep the vibrator is mechanically raised, and it would reach a depth of around 5m at the end of the sweep. Once a sweep has been completed, the vibrator is lowered again to its starting depth, ready for a subsequent sweep.

Varying the depth of the vibrator such that constructive interference occurs at all frequencies during the sweep leads to an increased amplitude at all frequencies. It is possible to double the amplitude at all frequencies in this way.

When processing seismic data obtained using a swept-depth source of the present invention, it is necessary to allow for the variation in depth during the processing. This does not present any significant problem, and conventional methods of long-sweep deconvolution may be employed provided that the source signature estimation method correctly includes the movement of the seismic energy source.

A conventional seismic survey vessel is equipped with a mechanism 7 for lowering a seismic energy source into the water, and for subsequently removing it from the water upon completion of the survey. It will also have a control means for operating the seismic source. All that is required in order to put the present invention into effect is to provide the raising/lowering mechanism 7 with a suitable control means (not shown) for continually varying the depth of the marine vibrator during a sweep. Where the raising/lowering mechanism is computer-controlled, for example, this can be done

simply by programming the computer to raise the seismic source in a predetermined manner. For example, the vibrator could be raised at a predetermined, constant rate, or it could be raised at a rate chosen such that the depth of the vibrator is a constant ratio to the wavelength of the energy being emitted by the vibrator.

In order to facilitate keeping the ratio between the depth of the vibrator and the wavelength of the energy emitted from the vibrator substantially constant, it is possible to use a single control means to control both the emission of energy from the vibrator and the depth of the vibrator. For example, a suitably programmed computer could control the raising/lowering mechanism and also control the wavelength of energy emitted from the vibrator.

A marine vibrator typically has a mass of several tons. The boat 4 is therefore preferably provided with a support rail 6 to guide the vibrator when it is lifted during a sweep.

This embodiment of the present invention is not limited to use with a single seismic source. It is common for a marine seismic survey to be carried out using a lateral array of seismic sources, for example a linear array of 6 vibrator units arranged at a common depth. It would be possible to carry out the invention using such an array of seismic sources, with the depth of the array being varied during a sweep. This would enable all the advantages of the use of a lateral array of seismic sources to be retained, as well as achieving the advantages of the present invention.

In a second embodiment of the invention, emission of seismic energy at different depths during a sweep is obtained not by varying the depths of the source(s) during a sweep, but by using a vertical array of two or more marine vibrators. This embodiment of the invention again enhances the amplitude of the low-frequency energy spectrum of the signal obtained by interference between the direct signal and the ghost signal, while retaining the amplitude at high-frequencies.

One example of this embodiment of the invention uses a marine vibrator array having 6 vibrators. When the array is in use, three of the vibrators are deployed at a depth of 12m, and three at a depth of 6m. The vibrators at a depth of 12m have a notch frequency at 62.5Hz and have peak frequencies at 31.25Hz and 93.75Hz. The vibrators arranged at a depth of 6m have a ghost frequency at 125Hz, and have a peak frequency at 62.5Hz. Thus, a peak frequency of the vibrators at a depth of 6m is coincident with, and compensates for, a notch frequency of the vibrators at a depth of 12m. The resultant amplitude spectrum of the overall signal of this array (that is, the combination of the direct signal and the ghost signal) demonstrates both the high amplitude at low frequencies associated with the vibrators at a depth of 12m, but retains the high frequency response of the vibrators at a depth of 6m.

It should be noted that reconfiguring the array from a horizontal array of 6 vibrators to a vertical array having three vibrators at a depth of 6m and three vibrators at a depth of 12m has not changed the total energy that is emitted by the array. The energy has, however, been redistributed within the spectrum of the overall signal, to improve the low-frequency amplitude while having minimal effect on the amplitude at high frequencies.

In the above example, although the array included 6 vibrators they were positioned at only two different depths. In a vertical array of 6 vibrator units it is, however, possible to position units at different depths so as to optimise the energy spectrum of the output signal. The two principal characteristics to consider are the low-frequency amplitude, and the flatness of the amplitude of the spectrum from the first peak position to the highest frequency required in the survey (hereinafter the "spectral flatness").

Calculation of the output spectrum of a vertical array of 6 vibrators is straightforward in principle. It is first necessary to calculate the amplitude spectrum of the ghost filter for each vibrator using equation (3). The 6 separate spectra, one for each vibrator, are then summed to arrive at the overall spectrum of the array.

Once the overall spectrum has been computed for the array, its properties can be investigated by calculating one or more parameters of the overall amplitude spectrum. For example, the overall amplitude spectrum can be integrated between, for example, 10 and 35Hz to establish the low-frequency amplitude. It is alternatively possible to calculate the inverse of the standard deviation of the amplitude spectrum between, for example, 25 and 80Hz in order to calculate the spectral flatness. As a further alternative, a parameter indicative of both the spectral flatness and the amplitude at low frequencies could be calculated. (The bandwidths 10 to 35Hz and 25 to 80Hz given in the above example are chosen as examples, and can be adjusted to conform to the requirements of any particular survey).

Once the value of a parameter has been calculated for one set of depths for the vibrators, the depth of one or more of the vibrators is changed, the overall amplitude spectrum re-calculated, the parameter re-calculated, and its value for the new depths compared with its previous value. This procedure is then repeated for every possible combination of depths for the vibrators or, alternatively, until a combination of depths that gives an acceptable value for the parameter is obtained.

The optimisation is performed on combinations of ghost filters, and is independent on the vibrator sweep signature. This is acceptable because convolution and super-position are commutative relations – that is:

$$\{g_1(t)*s(t)\}+\{g_2(t)*s(t)\}+\{g_3(t)*s(t)\}+\{g_4(t)*s(t)\}+\{g_5(t)*s(t)\}+\{g_6(t)*s(t)\} \qquad (4)$$
$$=s(t)*\{g_1(t)+g_2(t)+g_3(t)+g_4(t)+g_5(t)+g_6(t)\}$$

In equation (4), $g^n(t)$ represents the time-domain ghost filter associated with the n^{th} vibrator unit, $s(t)$ is the time domain sweep signature, and the * represents convolution in the time domain. The optimisation is independent of the sweep signature, so that the bandwidth over which the optimisation norms are calculated should be set to be within the bandwidth of the sweep.

In some cases, it is possible to choose the depths of the marine vibrator so as to maximise a single parameter such as the amplitude at low frequencies or the spectral flatness. More generally, however, the amplitude at low frequencies and the spectral flatness are both important, and it is necessary to choose the depths of the marine vibrators to provide acceptable values for both these parameters. In this case, once the values for the two parameters have been calculated, they are scaled within their respective ranges. The scaled values are then added together, and the depths of the vibrators are chosen to maximise the value of this sum.

In an example, the array has 6 marine vibrators. The depth of each of the vibrators is allowed to vary between 1m and 15m, in steps of 1m. This gives a total of 38760 unique depth combinations.

The process of calculating the amplitude spectra for each one of these depth combinations, calculating the values of the two parameters of low frequency amplitude and spectral flatness for each combination, and choosing the optimal array configuration takes only a few minutes to run on a desk top computer.

Table 1 illustrates examples of the results of the optimisation process.

Table 1

Optimisation Parameter	Depth of Vibrator Number:					
	1	2	3	4	5	6
Low-Frequency Amplitude (10-35 Hz)	15 m	15 m	15 m	15 m	15 m	15 m
Spectral Flatness (25-85 Hz)	2 m	6 m	7 m	7 m	11 m	15 m
Optimised Sum	7 m	7 m	7 m	7 m	12 m	15 m

The overall output spectra calculated for the 3 arrays shown in table 1 are shown in Figure 8, as traces (a), (b) and (c) respectively. Trace (d) in Figure 8 shows the overall amplitude spectrum for a horizontal array having 6 vibrator units all at a depth of 6m, for comparison.

The first array given in table 1 shows that the amplitude at low frequencies is, as expected, maximised by placing all 6 vibrators at the lowest possible depth of 15m. This arrangement is, however, unsatisfactory as regards the flatness of the spectrum, since it creates a notch frequency at approximately 50Hz as shown in trace (a) of Figure 8.

The overall spectrum of the second configuration given in table 1 is shown as trace (b) in Figure 8, and it will be seen that this does indeed achieve good spectral flatness over most of the range between 25 to 85 Hz, although there is some tailing off above 80Hz. It will be seen, however, that the amplitude at low frequencies falls away markedly. This is, of course, to be expected since depths of the vibrators were chosen to maximise the spectral flatness, without consideration of the low-frequency amplitude.

Trace (c) in Figure 8 shows the results for the third vibrator configuration of table 1, in which the depths of the vibrators have been chosen to optimise both the amplitude at low frequency and the flatness of the spectrum. It will be seen that the spectrum produced by this arrangement has a greater amplitude at low frequencies than trace (b), at the expense of a slight deterioration in the flatness of the spectrum over the range 25-80Hz.

It will be seen that trace (c) clearly has greater amplitude at low frequencies and an improved spectral flatness compared with the spectrum shown in trace (d) for a conventional horizontal array of 6 vibrators all at a depth of 6m.

The above results show that, by moving an array of six marine vibrators from a depth of 6m to a depth of 15, the amplitude in the frequency range 10-35Hz increases by up to 6dB. At higher frequencies, the amplitude of the spectrum of the array at a depth of 15m falls off because of the 50Hz ghost notch. The array in which the depths of the vibrators are chosen to maximise the spectral flatness shows an increase of 0-3dB over the conventional array at a depth of 6m in the frequency range 10-25Hz. Above this frequency range, the amplitude of the overall spectrum varies by less than 1 dB while the conventional array at a depth of 6m increases by 4dB owing to the presence of the

peak frequency at 62.5Hz. The array configuration in which the depths of the vibrators are chosen so as to optimise both the amplitude at low frequencies and the spectral flatness shows an increase in amplitude of up to 4dB between 10 and 35Hz. The amplitude of the spectrum varies only fractionally more than that of the array in which the depths are chosen specifically to maximise the spectral flatness.

The positions of the vibrators in the third array shown in table 1 are obtained by summing the optimisation norms for the low frequency amplitude and the spectral flatness. Although each of the optimisation norms has been scaled within its own range, this is not sufficient to eliminate bias in the summation process. If the distribution of one of the optimisation parameters within its range is non-linear, then the resultant summation will be biased towards one of the parameters. It will be seen in Figure 8 that the optimised amplitude, trace (c), appears to be biased towards the spectral flatness characteristic in preference to the low-frequency amplitude.

In a preferred embodiment of the invention, therefore, a bias factor is applied in the summation process. A simple linear bias factor is applied in the optimisation, and this can be set to a value between –1 and 1 to bias the summation towards the spectral flatness characteristic or towards the low-frequency amplitude characteristic. The bias takes the form of:

$$\begin{aligned} &\beta=0, && \xi=F_N+L_N \\ &1\geq\beta>0, && \xi=F_N(1-\beta)+L_N \\ &-1\leq\beta<0, && \xi=F_N+L_N(1-|\beta|) \end{aligned} \tag{5}$$

In Equation 5, F_N and L_N represent the normalised spectral flatness and the normalised low-frequency amplitude respectively. β is the bias coefficient, and ξ is the optimisation sum.

The optimisation process was repeated using a bias coefficient of $\beta = +0.5$ in an attempt to improve the amplitude at low frequency. The results are shown in table 2.

Table 2

Optimisation Parameter	Depth of Vibrator Number:					
	1	2	3	4	5	6
Low-Frequency Amplitude (10-35 Hz)	15 m	15 m	15 m	15 m	15 m	15 m
Spectral Flatness (25-85 Hz)	2 m	6 m	7 m	7 m	11 m	15 m
Optimised Biased Sum (β=+0.5)	7 m	7 m	8 m	11 m	15 m	15 m

The array shown in the first row of table 2 is the array that maximises the amplitude at low frequency, and the array shown in the second row provides the best spectral flatness. These arrays are the same as the arrays shown in the first two rows of table 1.

The array set out in the third row of table 2 is not, however, the same as the array shown in the third row of table 1, as a result of introducing the bias factor into the summation.

Figure 9 shows the overall amplitude spectrum of the signal (that is, the combination of the direct signal and the ghost signal) of the array of the third row of table 2. This is shown as trace (a). The amplitude spectrum of the array of the third row of table 1 is shown for comparison as trace (b), and the amplitude spectrum for a conventional horizontal array of 6 vibrators all at a depth of 6m is shown for comparison as trace (c). It will be seen that introducing a bias coefficient of $\beta = +0.5$, which reduces the weight of the spectral flatness during the summation process, has indeed resulted in a greater amplitude at low frequencies (10-35Hz). The amplitude at low frequencies of the spectrum of the "biased" array is increased by up to 2dB compared with the amplitude of the "unbiased" array, and by up to 5dB compared with the conventional horizontal array at a depth of 6m.

Trace (a) of Figure 10 shows the results of convolving trace (a) of Figure 9 with a 0.5dB/Hz earth loss filter. Trace (b) shows the amplitude spectrum for a conventional horizontal array of 6 vibrators each at a depth of 6m after convolution with a 0.5dB/Hz earth loss filter. The increased amplitude at low frequencies is readily evident in Figure 10.

It has been found that increasing the bias coefficient above $\beta = +0.5$ produces only a marginal increase in the amplitude at low frequency, but leads to a very severe loss of spectral flatness. It is therefore undesirable to use a bias factor significantly greater than $\beta = +0.5$.

The spectra of the vibrator arrays described in tables 1 and 2 were calculated using the assumption that the reflection coefficient at the sea surface is –1.0. It has however, been suggested that the reflection coefficient at the sea surface is typically lower than this, owing to the effect of the sea surface not being flat. For example, a more accurate value for the reflection coefficient at the sea surface might be between -0.85 and -0.80 for normal sea conditions under which seismic data are generally acquired.

Table 3 illustrates the results of varying the reflection coefficient at the sea surface between –1.00 and –0.05, in increments of 0.05. The results of table 3 were calculated using a bias coefficient of $\beta = +0.5$. The first row of table 3 therefore corresponds exactly to the third row of table 2.

Table 3

Reflection Coefficient	Depth of Vibrator Number:					
	1	2	3	4	5	6
-1.00	7 m	7 m	8 m	11 m	15 m	15 m
-0.95	7 m	7 m	8 m	11 m	15 m	15 m
-0.90	7 m	7 m	8 m	11 m	15 m	15 m
-0.85	7 m	7 m	8 m	11 m	15 m	15 m
-0.80	7 m	7 m	8 m	11 m	15 m	15 m
-0.75	7 m	7 m	8 m	11 m	15 m	15 m
-0.70	7 m	7 m	8 m	11 m	15 m	15 m
-0.65	7 m	7 m	8 m	11 m	15 m	15 m
-0.60	7 m	7 m	8 m	11 m	15 m	15 m
-0.55	8 m	9 m	9 m	15 m	15 m	15 m
-0.50	8 m	8 m	9 m	15 m	15 m	15 m
-0.45	8 m	8 m	9 m	15 m	15 m	15 m
-0.40	8 m	8 m	9 m	15 m	15 m	15 m
-0.35	8 m	8 m	9 m	15 m	15 m	15 m
-0.30	8 m	8 m	9 m	15 m	15 m	15 m
-0.25	8 m	8 m	9 m	15 m	15 m	15 m
-0.20	8 m	8 m	9 m	15 m	15 m	15 m
-0.15	8 m	8 m	9 m	15 m	15 m	15 m
-0.10	8 m	8 m	9 m	15 m	15 m	15 m
-0.05	8 m	8 m	9 m	15 m	15 m	15 m

It will be seen that the calculated positions of the vibrators in the vertical vibrator array are relatively insensitive to the magnitude of the reflection coefficient at the sea surface, particularly within the range of the coefficient that is associated with typical conditions for a marine seismic survey.

The process for calculating the amplitude spectrum of the vertical array of vibrators of the invention has ignored interactions between vibrator units. This assumption is believed to be reasonable, since it has been reported that vibrator units interact only very weakly.

Although the vertically distributed vibrator array described above contains 6 marine vibrators, the invention is not limited to an array of 6 vibrators. An array can in principle have any number of vibrators above two, and preferably has between 4 and 6 vibrators.

A conventional horizontal vibrator array consisting of a number of vibrator units arranged in a horizontal line is operated such that it is oriented perpendicular to the direction of emission of seismic energy. The directivity of a conventional horizontal array is such that constructive interference occurs most efficiently along a vertical in-line plane (that is, a vertical plane that is perpendicular to the array and is parallel to the central direction of emission of seismic energy. Secondary constructive anti nodes are formed along planes that are parallel to the in-line direction, but which are offset in the cross-line direction. Partial or complete destructive interference occurs at all other azimuths and take-off angles. The output signature of the vibrator array is extremely stable with regard to take-off angle within the in-line plane.

Reconfiguring the array, to a vertical array of the type used in the present invention, will have a significant effect on the directivity of the array. The primary plane of constructive interference would not longer be a vertical plane, but would be a horizontal plane passing through the mean depth of the array. The output signature of the array will vary significantly with take-off angle.

In a further embodiment of the invention, the marine vibrators in the array are not arranged exactly one above the other, but the vibrator units mounted at shallow depths are placed further back from the vessel than the vibrator units at greater depths. For example, in an array with vibrators at depths of 7m, 7m, 8m, 11m, 15m, and 15m, the vibrators 10 at a depth of 7m and the vibrator 11 at a depth of 8m could be arranged further back from the vessel 4 than the vibrator 12 at a depth of 11m and the vibrators 13 at a depth of 15m. This can be done simply by suspending a boom 14 from the vessel's raising/lowering mechanism 5, and suspending the vibrators at shallow depths from one end of the boom 14 and the vibrators at greater depths from the upper end of the boom 14.

It is possible for the lateral separation y between the vibrators of the array to be greater than the difference in depth z between the shallowest vibrator 10 and the deepest vibrator 13. This would reduce the problem of the variation of the output sweep signature with the take-off angle.

Introducing a vertical separation between the marine vibrators in an array has the effect of introducing a phase shift between the energy emitted from two vibrators at different depths. In order to prevent such a phase shift occuring, in one embodiment of the invention the start time of the sweep of the deeper marine vibrators is delayed compared to the start time of the sweep of the shallower vibrator units. The delay time is preferably substantially equal to the time taken for seismic energy emitted by the shallower vibrators to reach the deeper vibrators, so that the deeper marine vibrators begin their sweep at the same time as the energy emitted by the shallower marine vibrators at the start of their sweep reaches the deeper vibrators. The phase shift between the deeper vibrators and the shallower vibrators is thus eliminated.

In the case of the array shown in Figure 11, the two vibrators 10 at a depth of 7m would be the first marine vibrators to be swept. The start of the sweep of the vibrator 11 at a depth of 8m would be delayed by approximately the time taken for seismic energy emitted from the vibrators 10 at a depth of 7m to travel 1m and reach the vibrator 11 at a depth of 8 metres.

Similarly, the start of the sweep of the marine vibrator 12 at a depth of 11m would be delayed, relative to the start of the sweep of the two vibrators 10 at a depth of 7m, by approximately the time taken for seismic energy emitted from the upper vibrators 10 to travel a distance of 4m, and the start of the sweep of the vibrators 13 at a depth of 15m will be delayed, again relative to the start of the sweep of the vibrators 10 at a depth of 7m, by approximately the time taken for seismic energy to travel a distance of 8m.

In an alternative embodiment of the invention, the sweeps of all the marine vibrators in the array are started at the same time, and the effects of the phase difference between energy emitted from vibrators at different depths is taken into account during the analysis of the recorded data. This is done by correlating the recorded data separately for the individual vibrators in the array, and including phase differences appropriate to the different depths of the vibrators in the array in the subsequent processing of the data.

CLAIMS:

1. A method of seismic surveying using one or more marine vibrators, the method comprising emitting seismic energy at one or more different depths during a sweep.

2. A method as claimed in claim 1 and comprising emitting seismic energy from an array of marine vibrators, the array of marine vibrators comprising at least a first vibrator at a first depth and a second vibrator at a second depth greater than the first depth.

3. A method as claimed in claim 2 wherein the first vibrator of the array is displaced with respect to the second vibrator in the direction of emission of seismic energy.

4. A method as claimed in claim 2 or 3 and further comprising starting emission of seismic energy from the second vibrator a pre-determined time after starting emission of seismic energy from the first vibrator.

5. A method as claimed in claim 4 wherein the pre-determined time is substantially equal to the time taken for seismic energy emitted from the first vibrator to reach the second vibrator.

6. A seismic surveying arrangement comprising: a vessel; a source of seismic energy; and means for suspending the source of seismic energy from the vessel; wherein the source of seismic energy is an array of two or more marine vibrators, the array being suspended in use such that a first vibrator is disposed at a first depth and a second vibrator is disposed at a second depth greater than the first depth.

7. An arrangement as claimed in claim 6 wherein the first vibrator is displaced with respect to the second vibrator in the direction of emission of seismic energy.

8. An arrangement as claimed in claim 6 or 7 wherein the array includes four to six marine vibrators.

9. An arrangement as claimed in claim 8 and comprising four vibrators at a depth of substantially seven metres, one vibrator at a depth of substantially twelve metres and one vibrator at a depth of substantially fifteen metres.

10. An arrangement as claimed in claim 8 and comprising two vibrators at a depth of substantially seven metres, one vibrator at a depth of substantially eight metres, one vibrator at a depth of substantially eleven metres, and two vibrators at a depth of substantially fifteen metres.

11. A method of calculating the preferred depths for seismic sources in an array of a plurality of seismic sources, the method comprising the steps of:

a) assigning a depth to each seismic source in the array;
b) for each seismic source in the array, obtaining the amplitude spectrum of seismic energy emitted by the seismic source;
c) summing the results of step (b) to obtain the amplitude spectrum of seismic energy emitted by the array of seismic sources; and
d) generating a parameter indicative of a property of the amplitude spectrum of seismic energy emitted by the array of seismic sources.

12. A method as claimed in claim 11 wherein step (b) comprises summing energy received at a point directly from the seismic source and energy received at the point after reflection from the sea surface.

13. A method as claimed in claim 11 or 12 wherein the parameter is indicative of the amplitude of the spectrum of the array in a first frequency band.

14. A method as claimed in claim 11 or 12 wherein the parameter is indicative of the variation of the amplitude of the spectrum of the array in a second frequency band.

15. A method as claimed in claim 11 or 12 wherein the parameter is the sum of a first parameter indicative of the amplitude of the spectrum of the array in a first frequency band and a second parameter indicative of the variation of the amplitude of the spectrum of the array in a second frequency band.

16. A method as claimed in claim 11 or 12 wherein the parameter is a weighted sum of a first parameter indicative of the amplitude of the spectrum of the array in a first frequency band and a second parameter indicative of the variation of the amplitude of the spectrum of the array in a second frequency band.

17. A method as claimed in any of claims 11 to 16 and further comprising the steps of:

e) assigning a new depth to one or more of the seismic sources; and

f) repeating steps (b), (c) and (d).

18. A method as claimed in any of claims 11 to 17 wherein each seismic source is a marine vibrator.

19. A method of seismic surveying as claimed in claim 1, comprising varying the depth of a marine vibrator while the marine vibrator is emitting seismic energy.

20. A method as claimed in claim 19 and further comprising the step of varying the frequency of the seismic energy emitted from the marine vibrator.

21. A method as claimed in claim 20 wherein the frequency of the seismic energy emitted from the marine vibrator is varied such that the ratio of the depth of the marine vibrator to the wavelength of the seismic energy emitted from the marine vibrator is substantially constant.

22. A method as claimed in claim 21 wherein the ratio of the depth of the marine vibrator to the wavelength of the seismic energy emitted from the marine vibrator is approximately one quarter.

23. A method as claimed in any of claims 19 to 22 wherein the depth of the marine vibrator is reduced while the marine vibrator is emitting seismic energy.

24. A method as claimed in claim 23 wherein the initial depth is 50m, the initial frequency is 7.5Hz, the final depth is 5m and the final frequency is 75Hz.

25. A seismic surveying arrangement comprising: a vessel; a marine vibrator; means for suspending the marine vibrator from the vessel; a first control means for causing the marine vibrator to emit seismic energy; and a second control means for varying the depth of the marine vibrator.

26. An arrangement as claimed in claim 25 wherein the second control means is adapted to control the depth of the marine vibrator on the basis of the wavelength of the seismic energy emitted by the marine vibrator.

27. An arrangement as claimed in claim 26 wherein the second control means is adapted to control the depth of the marine vibrator such that the ratio of the depth of the marine vibrator to the wavelength of the seismic energy emitted from the marine vibrator is substantially constant.

28. An arrangement as claimed in claim 27 wherein the second control means is adapted to control the depth of the marine vibrator such that the ratio of the depth of the marine vibrator to the wavelength of the seismic energy emitted by the marine vibrator is approximately one quarter.

29. An arrangement as claimed in any of claims 25 to 28 wherein the first control means is the second control means.

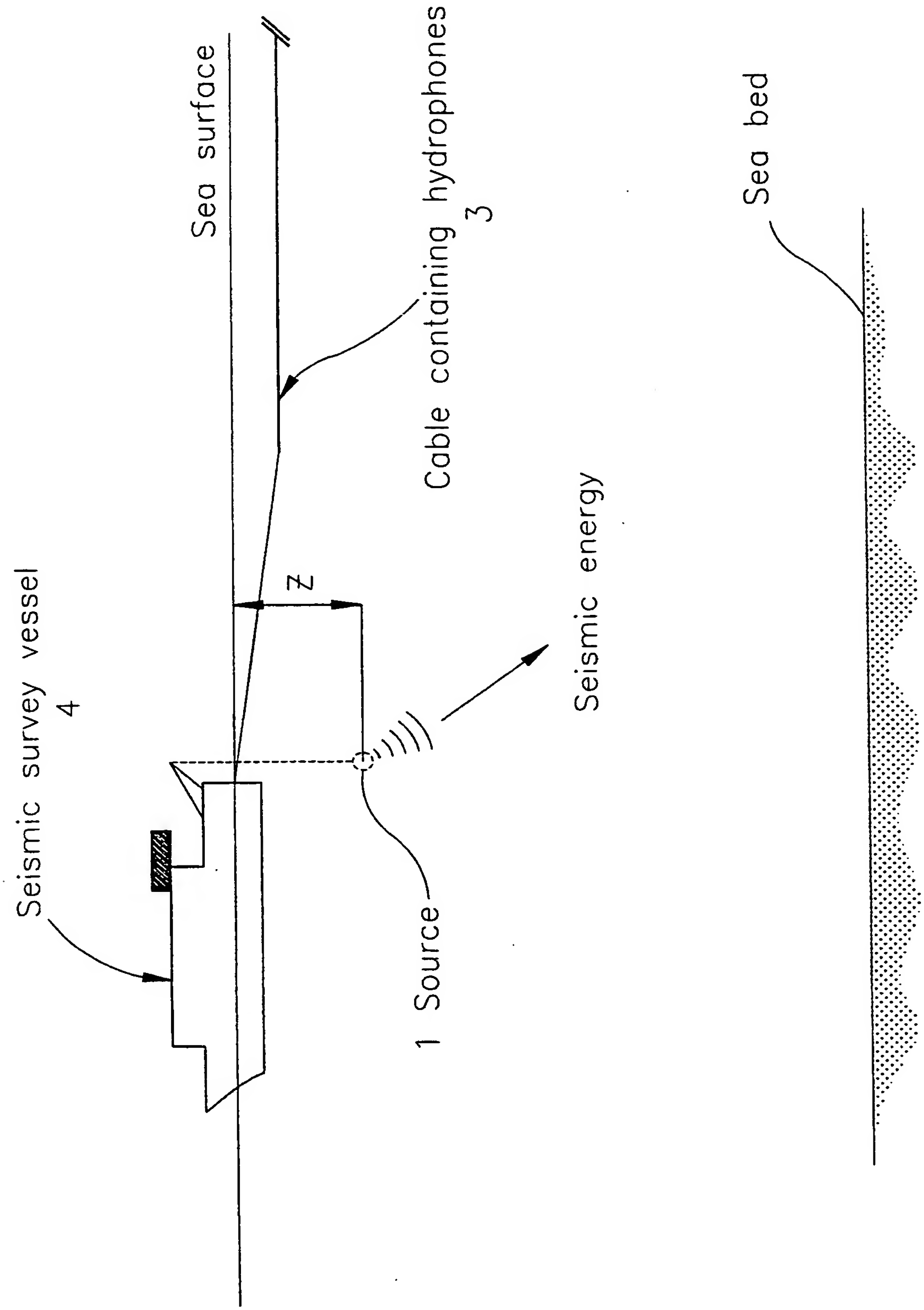
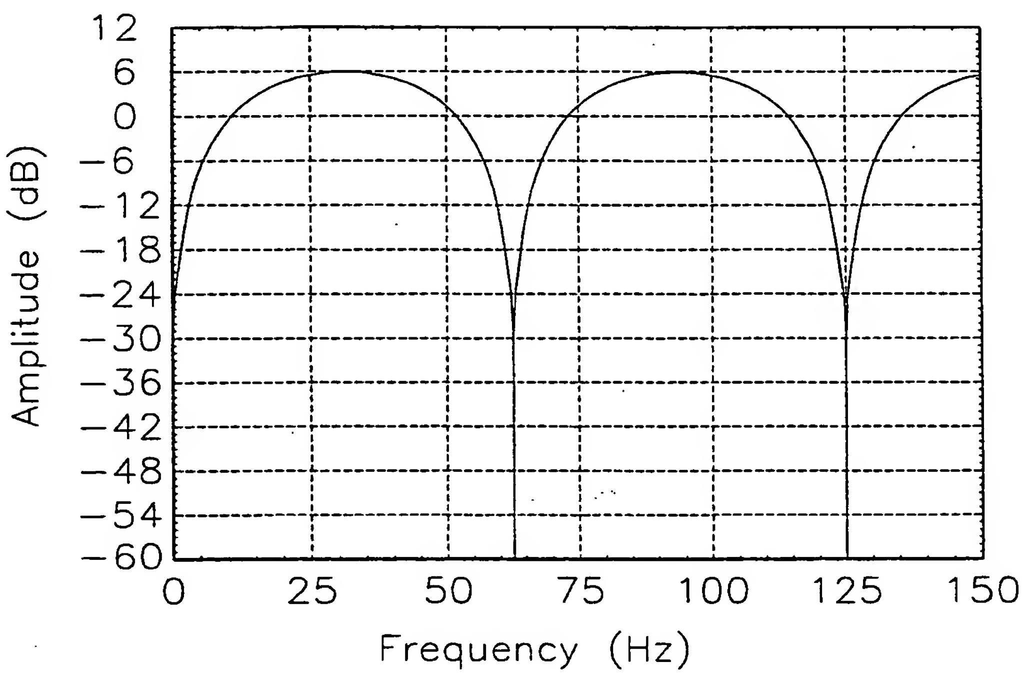

Sea surface
Cable containing hydrophones
3
Sea bed
Seismic survey vessel
4
Z
Seismic energy
1 Source

FIG 1



Amplitude spectrum of a 12m Ghost filter

FIG 2

Spectrum of Ghost filter : depth = 5 metres

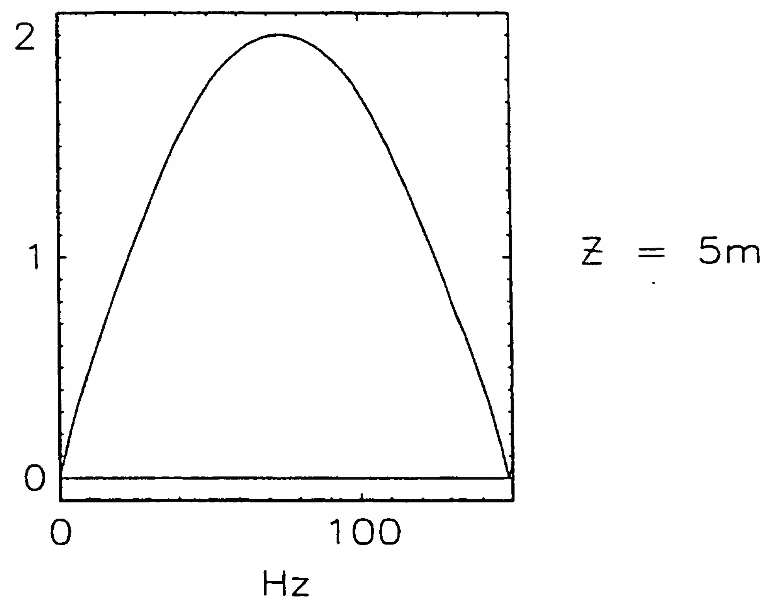


FIG 3a

Spectrum of Ghost filter : depth = 50 metres

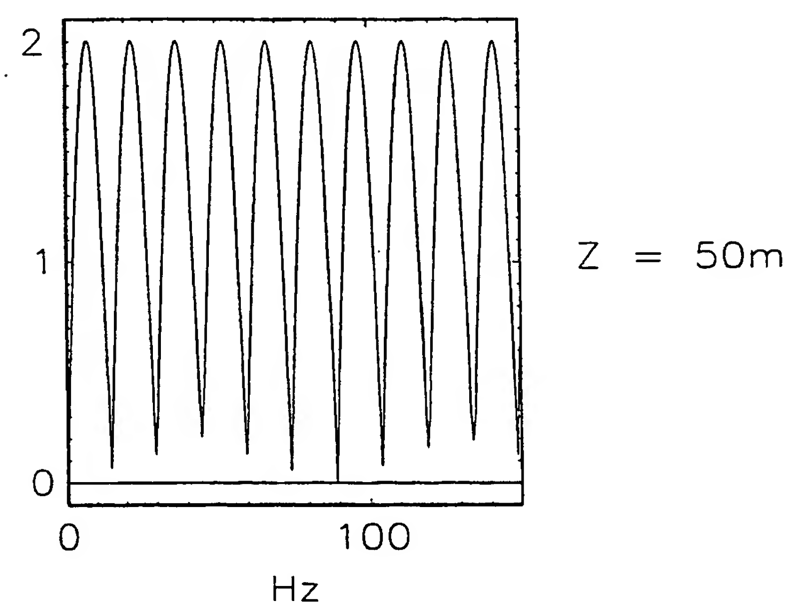
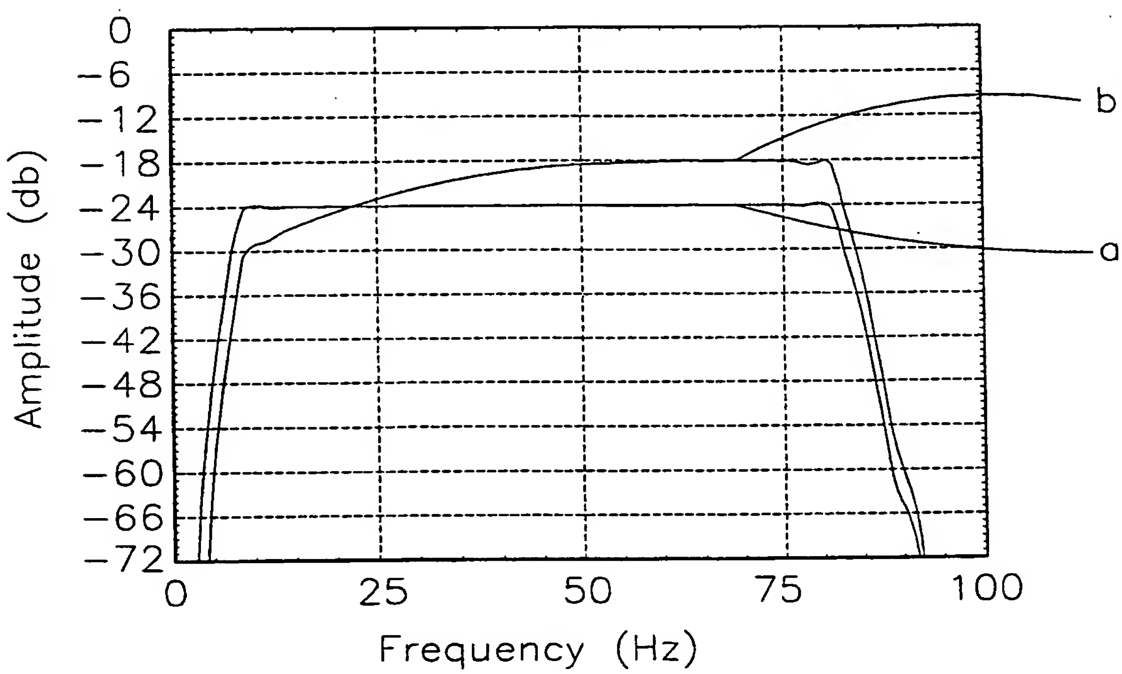
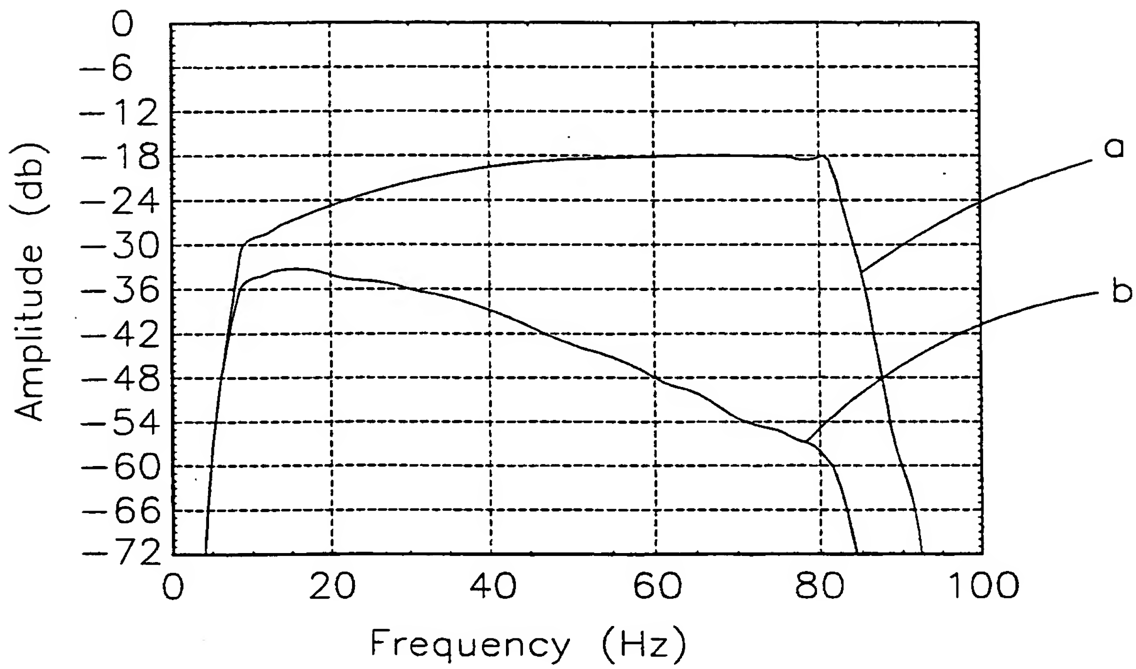


FIG 3b



5–85Hz Sweep(a) v. Convolution with 6m Ghost filter(b)

FIG 4



5-85Hz Sweep at 6m depth(a)v. convolution with 0.5 dB/Hz Q filter(b)

FIG 5

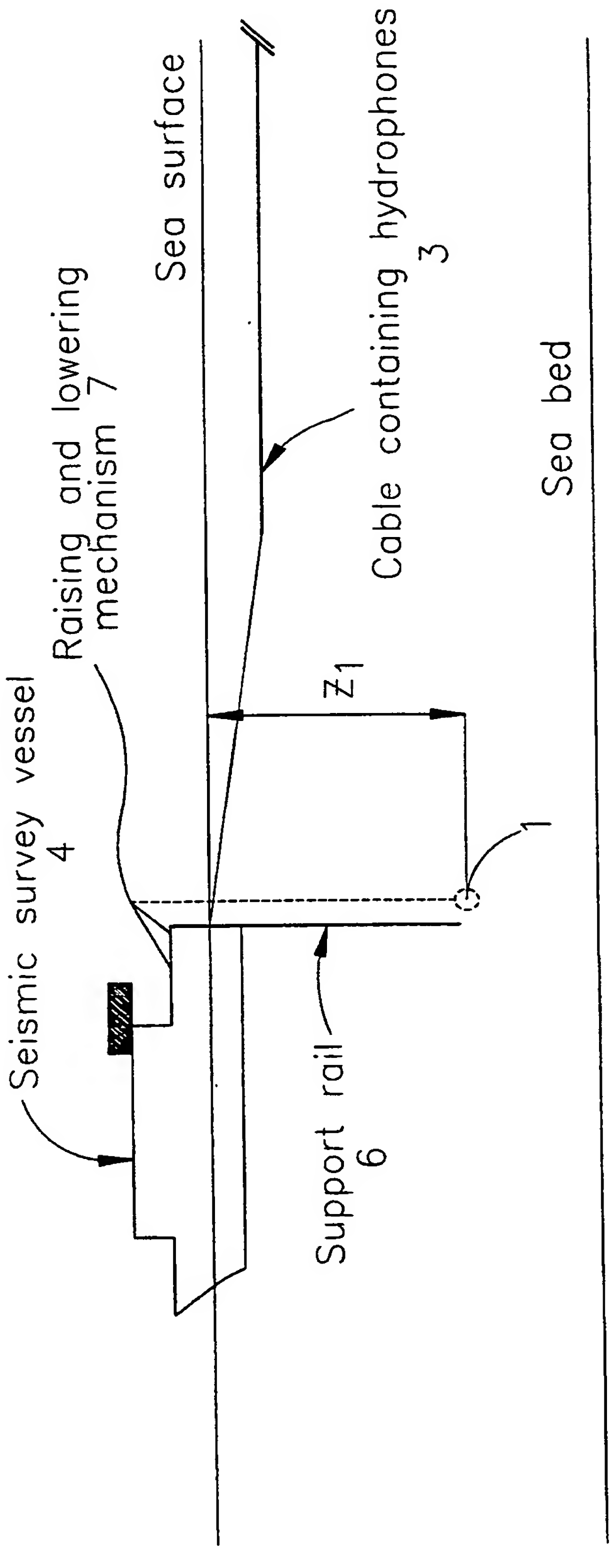

Sea surface
Cable containing hydrophones
3
Raising and lowering
mechanism 7
Sea bed
Seismic survey vessel
4
z_1
1
Support rail
6

FIG 6

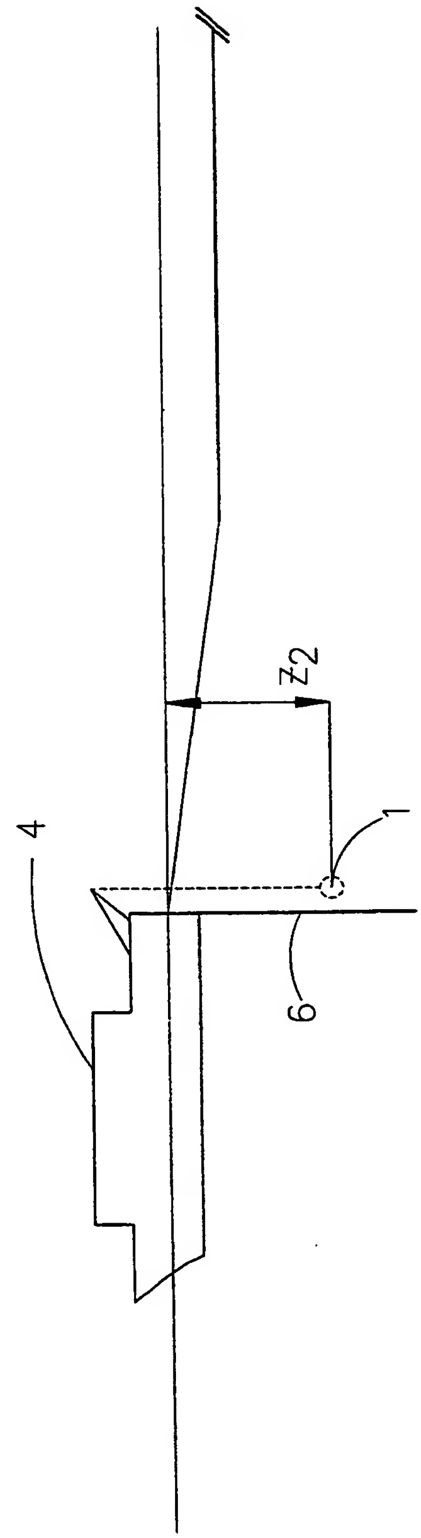
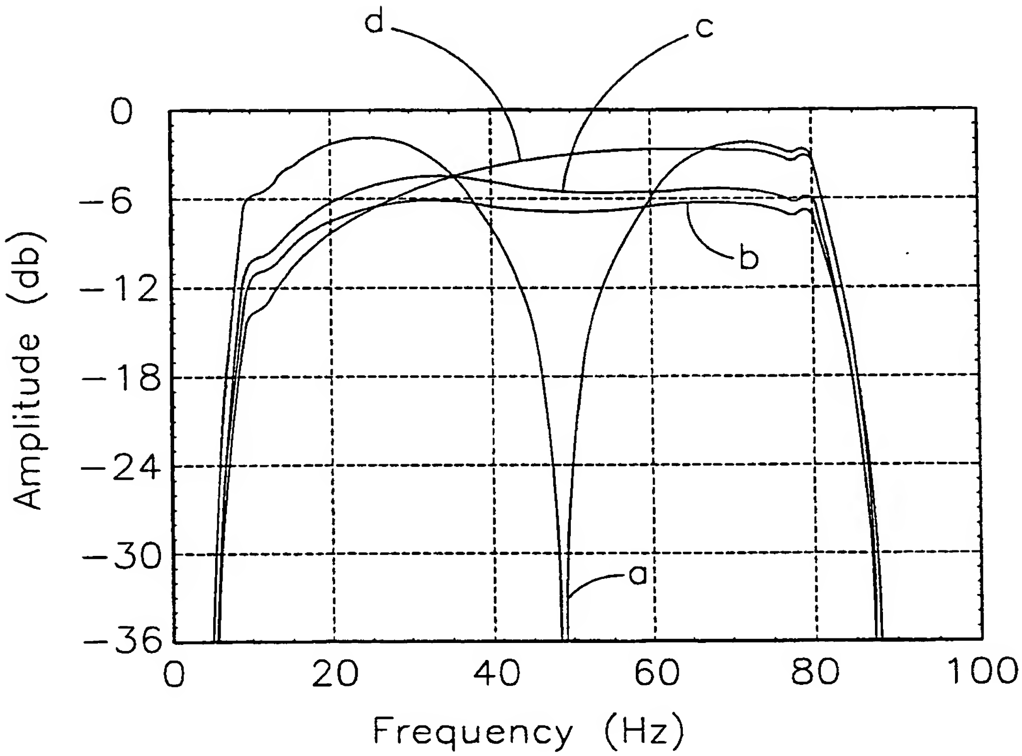
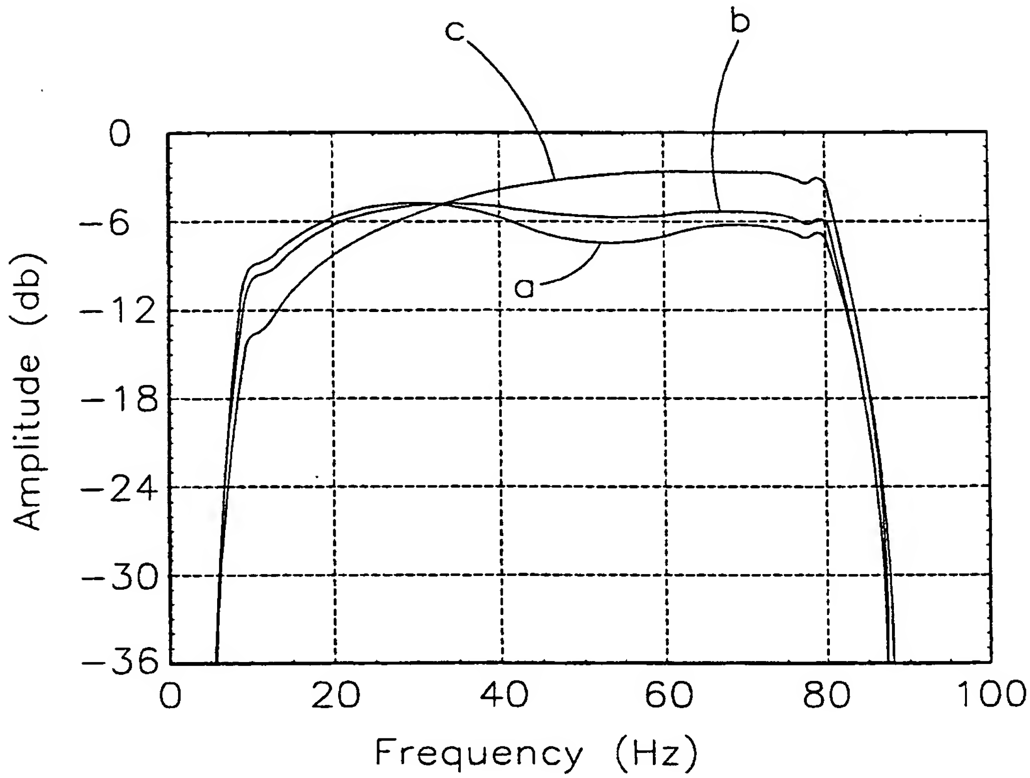

4
z_2
1
6

FIG 7



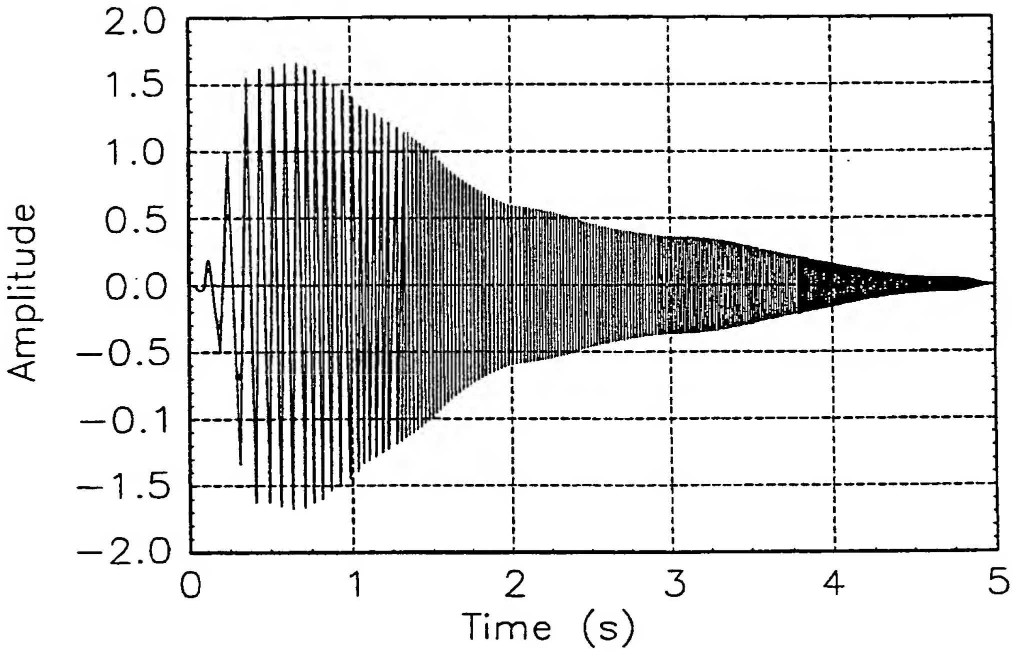
5–85Hz Sweep at 6m depth (d)v.Optimisation for:
Low freq.Power(a),Spectral flatness (b),
Optimised summation(c)

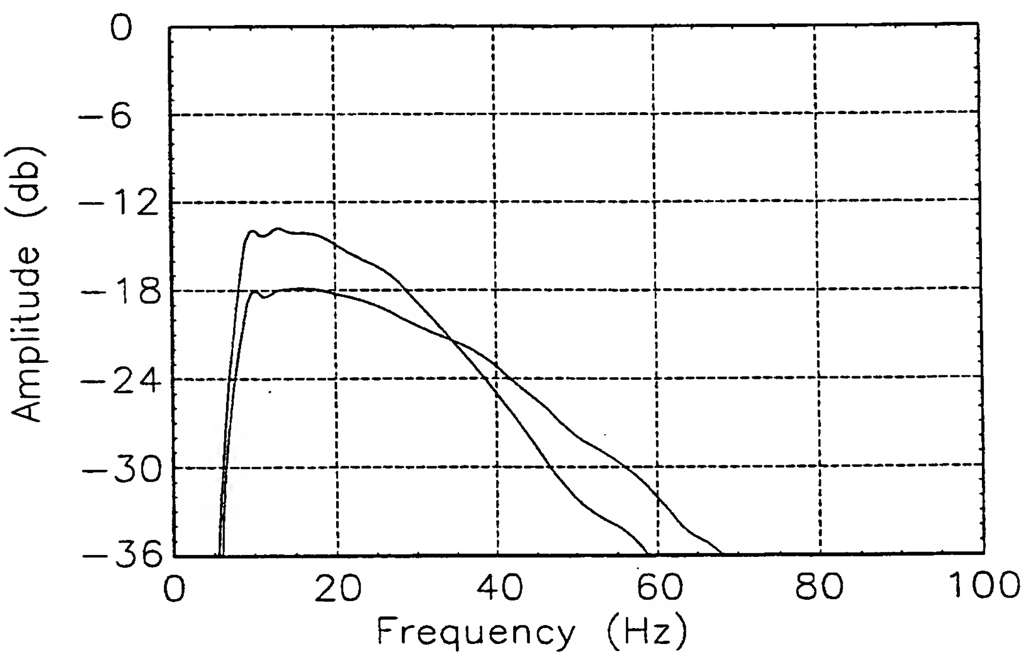
FIG 8



5−85Hz Sweep at 6m depth (c)v.Unbiased summation (b) and Biased summation β=+0.5(a)

FIG 9





5−85Hz Sweep at 6m depth (b)v.Biased optimisation summation (a)

FIG 10

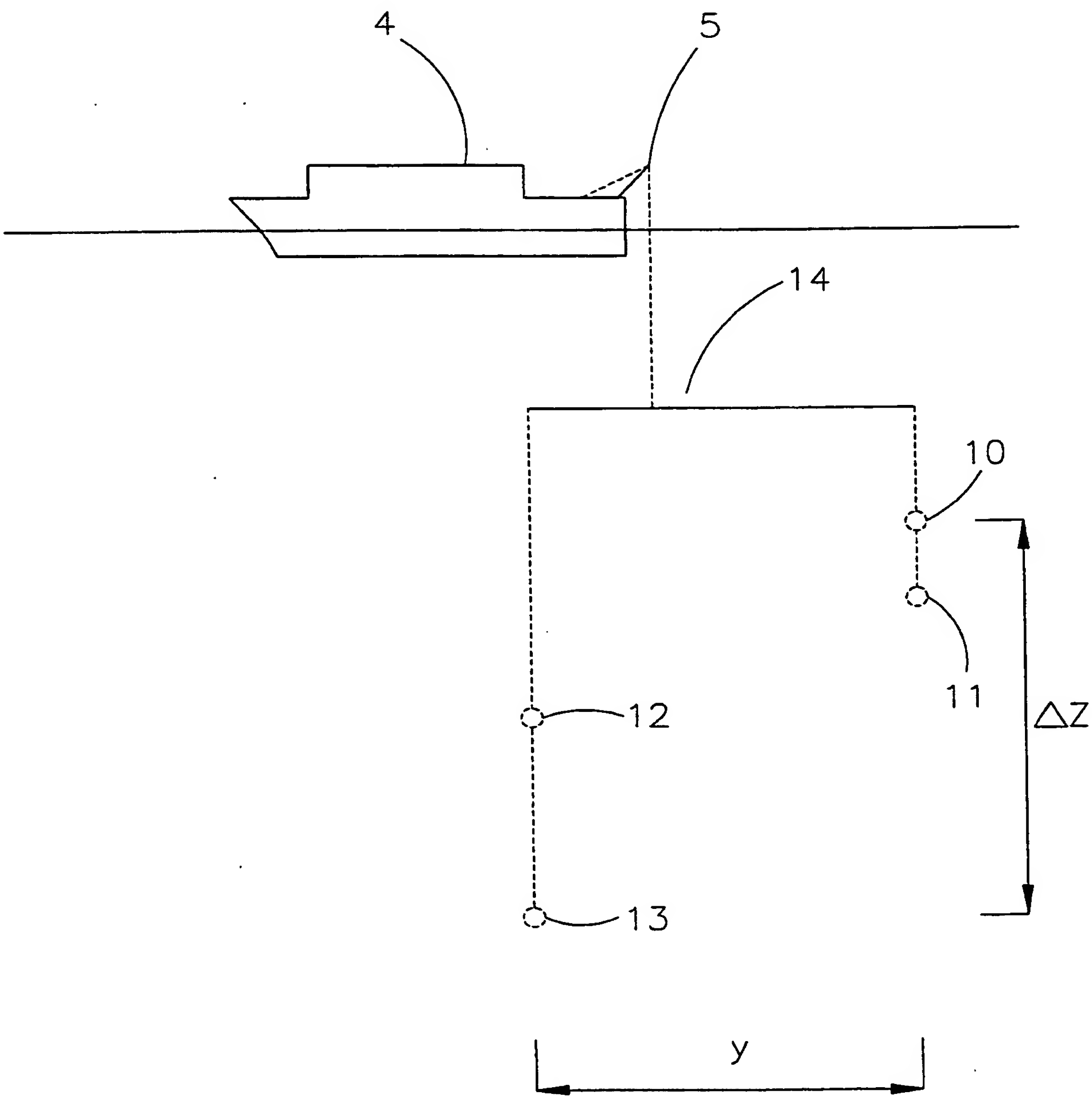


FIG 11

INTERNATIONAL SEARCH REPORT

Inte onal Application No
PCT/GB 00/03218

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01V1/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 469 404 A (BARBER HAROLD P ET AL) 21 November 1995 (1995-11-21) column 3, line 62 -column 4, line 21 column 4, line 61 -column 5, line 48 column 8, line 2 - line 10 ---	1-7
X	GB 2 148 503 A (SIESMOGRAPH SERVICE) 30 May 1985 (1985-05-30) the whole document ---	1,6,11
X	GB 2 176 605 A (EXXON PRODUCTION RESEARCH CO) 31 December 1986 (1986-12-31) page 2, line 55 -page 3, line 11 page 3, line 46 - line 48 page 6, line 3 - line 12 ---	25

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 November 2000	24/11/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Lorne, B

1

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/03218

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97 06452 A (HYDROACOUSTIC INC ;BOUYOUCOS JOHN V (US)) 20 February 1997 (1997-02-20) page 4, line 23 -page 5, line 3 page 9, line 1 - line 17; claims 1,7,9,11	1,6
X	US 4 727 956 A (HUIZER WILLEM) 1 March 1988 (1988-03-01) column 5, line 24 -column 6, line 25; claim 1	1,6
X	US 4 136 754 A (MANIN MICHEL) 30 January 1979 (1979-01-30) claim 1; figures 4A,4B	1,6-8
X	US 4 493 061 A (RAY CLIFFORD H) 8 January 1985 (1985-01-08) column 3, line 33 -column 4, line 31; claim 1	1,6-8

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte onal Application No
PCT/GB 00/03218

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			JP	59137876	A	08-08-1984
			NO	840159	A	20-07-1984
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